

CP Violation in $B^0 \rightarrow \eta' K^0$ and Status of SU(3)-related Decays

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We present measurements from Belle and BABAR of the time-dependent CP -violation parameters S and C in $B^0 \rightarrow \eta' K^0$ decays. Both experiments observe mixing-induced CP violation with a significance of more than 5 standard deviations in this $b \rightarrow s$ penguin dominated mode. We also compare with theoretical expectations and discuss the latest results for SU(3)-related decays which are useful for obtaining bounds on the expected values of S and C .

I. INTRODUCTION

Because of the large rate for the process, the decay $B^0 \rightarrow \eta' K^0$ has proved to be the most precise outside of the $c\bar{c}K^0$ system for determination of the value of $\sin 2\beta$ through time-dependent CP -violation measurements. The dominant process is a penguin (loop) decay where new physics can enter through additional particles in the loop. There have been many predictions for the Standard-Model (SM) and non-SM expectations for this and related processes [1, 2, 3, 4, 5].

We report new results from BABAR [6] and Belle [7]. Both of these analyses observe mixing-induced CP violation with a significance of more than 5 standard deviations. We compare the results with theoretical expectations, some of which use data (summarized below) for decays of B^0 mesons to pairs of isoscalar mesons.

II. STATUS OF $B^0 \rightarrow \eta' K^0$

When the decay $B^0 \rightarrow \eta' K^0$ was first observed [8], the measured branching was much larger than theoretical predictions involving naive factorization. The situation has changed substantially with more recent calculations. In QCD factorization calculations [2], it was pointed out that higher-order QCD corrections and slight tweaking of parameters can easily account for the large observed result, though theory errors are still large. In a paper involving QCD factorization, SCET and inputs from B -decay data, the explanation of the large rate is thought to come from “charming-penguins”, long-distance effects involving the $c\bar{c}$ in the loop. While the details of the explanation for the large rate still differ somewhat, the recent calculations account for the large observed branching fraction with predominantly penguin amplitudes and the contribution from tree or penguin amplitudes involving V_{ub} is small. This feature is important as will be seen below.

III. EXPERIMENTAL DETAILS

For these measurements, Belle uses a dataset with a luminosity of 492 fb^{-1} ($535 \times 10^6 B\bar{B}$ pairs). The corresponding numbers for BABAR are 349 fb^{-1} and $384 \times 10^6 B\bar{B}$ pairs.

Both experiments use five final states of $B^0 \rightarrow \eta' K_S^0$, denoted B_{CP} . Those with a $K_S^0 \rightarrow \pi^+ \pi^-$ decay use the decays $\eta' \rightarrow \rho^0 \gamma$ ($\eta'_{\rho\gamma}$), $\eta' \rightarrow \eta_{\gamma\gamma} \pi^+ \pi^-$ ($\eta'_{\eta(\gamma\gamma)\pi\pi}$), and $\eta' \rightarrow \eta_{3\pi} \pi^+ \pi^-$ ($\eta'_{\eta(3\pi)\pi\pi}$), where $\eta_{\gamma\gamma}$ and $\eta_{3\pi}$ denote the decays $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+ \pi^- \pi^0$, respectively. Those with a $K_S^0 \rightarrow \pi^0 \pi^0$ use $\eta'_{\rho\gamma}$ and $\eta'_{\eta(\gamma\gamma)\pi\pi}$. For the decays $B^0 \rightarrow \eta' K_L^0$, both experiments use the $\eta'_{\eta(\gamma\gamma)\pi\pi}$ mode while Belle additionally uses $\eta'_{\eta(3\pi)\pi\pi}$.

The quantities used in the analysis are similar for both experiments: a B -mass variable (denoted m_{ES} for BABAR), $\Delta E \equiv E_B^* - E_{\text{beam}}^*$ (the asterisk denotes center-of-mass quantities), variables that discriminate between spherical B -decay events and jetlike $q\bar{q}$ background, a tagging variable to determine the flavor of the “tag” B (B_{tag}), and the difference $\Delta t \equiv t_{CP} - t_{\text{tag}}$ of the proper decay times t_{CP} and t_{tag} of the CP and tag B mesons, respectively. Maximum-likelihood (ML) fits are used to distinguish signal from background and to determine the parameters S and C via the time dependence (for BABAR—the formula for Belle is similar)

$$F(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} [1 \mp \Delta w \pm (1 - 2w)(-\xi S \sin(\Delta m_d \Delta t) - C \cos(\Delta m_d \Delta t))] \quad (1)$$

where ξ is the CP eigenvalue of the final state (-1 for $B^0 \rightarrow \eta' K_S^0$, $+1$ for $B^0 \rightarrow \eta' K_L^0$). The upper (lower) sign denotes a decay accompanied by a B^0 (\bar{B}^0) tag, τ is the mean B^0 lifetime, Δm_d is the mixing frequency, and the mistag parameters w and Δw are the average and difference, respectively, of the probabilities that a true B^0 is incorrectly tagged as a \bar{B}^0 or vice versa.

For $B^0 \rightarrow \eta' K_S^0$ the ML fits for BABAR use all of the inputs mentioned above; Belle uses all except the event shape (they cut on this quantity). The fits for $B^0 \rightarrow \eta' K_L^0$ are similar except that one of the pair $[m_{ES}, \Delta E]$ is not used in the fit. Instead both experiments perform a constrained fit to the B -decay hypothesis since the K_L^0 energy is poorly measured.

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TABLE I: Summary for *BABAR* and Belle of the number of events entering the fits (N_{fit}), signal yields (N_{sig}), and fit values of S and C for each subsample. Belle reports $A = -C$.

Mode	N_{fit}	N_{sig}	<i>BABAR</i>		N_{fit}	N_{sig}	Belle	
			$-\xi S$	C			$-\xi S$	C
$\eta'_{\rho\gamma} K_{\pi^+\pi^-}^0$	11943	566 ± 30	0.56 ± 0.14	-0.24 ± 0.10	2870	794 ± 36	0.59 ± 0.15	0.14 ± 0.10
$\eta'_{\eta(\gamma\gamma)\pi\pi} K_{\pi^+\pi^-}^0$	664	224 ± 16	0.61 ± 0.23	-0.26 ± 0.14	634	363 ± 21	0.94 ± 0.22	-0.08 ± 0.13
$\eta'_{\eta(3\pi)\pi\pi} K_{\pi^+\pi^-}^0$	177	73 ± 9	0.89 ± 0.35	0.14 ± 0.25	125	100 ± 11	0.78 ± 0.47	-0.12 ± 0.27
$\eta'_{\rho\gamma} K_{\pi^0\pi^0}^0$	13915	133 ± 24	0.56 ± 0.41	0.15 ± 0.27	683	103 ± 15	-0.04 ± 0.38	-0.32 ± 0.28
$\eta'_{\eta(\gamma\gamma)\pi\pi} K_{\pi^0\pi^0}^0$	490	52 ± 9	0.84 ± 0.42	-0.26 ± 0.36	247	62 ± 9	1.27 ± 0.35	0.17 ± 0.38
$B^0 \rightarrow \eta' K_S^0$			0.62 ± 0.11	-0.18 ± 0.07			0.67 ± 0.11	0.03 ± 0.07
$\eta'_{\eta(\gamma\gamma)\pi\pi} K_L^0$	4199	204 ± 24	0.32 ± 0.28	0.08 ± 0.23	4606	393 ± 17	0.40 ± 0.25	-0.09 ± 0.17
$\eta'_{\eta(3\pi)\pi\pi} K_L^0$	—	—	—	—	585	62 ± 13	0.86 ± 0.73	-0.07 ± 0.44
$\eta' K^0$			$0.58 \pm 0.10 \pm 0.03$	$-0.16 \pm 0.07 \pm 0.03$			$0.64 \pm 0.10 \pm 0.04$	$0.01 \pm 0.07 \pm 0.05$

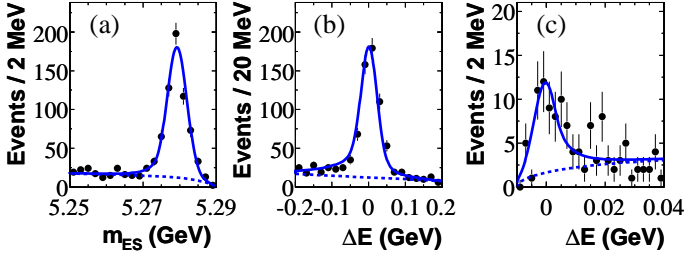


FIG. 1: Distributions of *BABAR* data projected onto (a) m_{ES} and (b) ΔE for $B^0 \rightarrow \eta' K_S^0$ candidates, and (c) ΔE for $B^0 \rightarrow \eta' K_L^0$ candidates. The solid lines show the full fit result and the dashed lines show the background contributions.

IV. RESULTS FROM BELLE AND *BABAR*

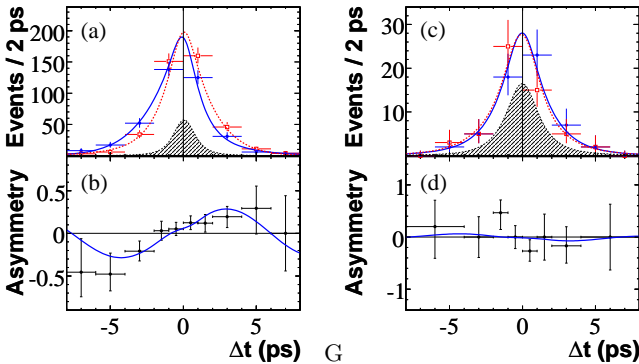


FIG. 2: *BABAR* projections onto Δt for (a) $B^0 \rightarrow \eta' K_S^0$ and (c) $B^0 \rightarrow \eta' K_L^0$ of the data (points with error bars for B^0 tags in red empty rectangles and \bar{B}^0 tags in blue solid circles), fit function (red dashed and blue solid lines for B^0 and \bar{B}^0 tagged events, respectively), and background function (black shaded regions). We show the asymmetry between B^0 and \bar{B}^0 tags for (b) $B^0 \rightarrow \eta' K_S^0$ and (d) $B^0 \rightarrow \eta' K_L^0$; the lines represent the fit functions.

To illustrate the samples, we show in Fig. 1 projection plots for the signals from *BABAR*. The results of the fits for both experiments for all subsamples are shown in Table I. The values of S are inconsistent with zero at the level of 5.5 standard deviations (σ) for *BABAR* and 5.6σ for Belle. C is consistent with zero for both experiments. Plots of the time-dependence for *BABAR* are shown in Fig. 2 and Belle in Fig. 3. The values of S and C for both experiments are now in good agreement with average values $S = 0.61 \pm 0.07$ and $C = -0.09 \pm 0.06$ [9].

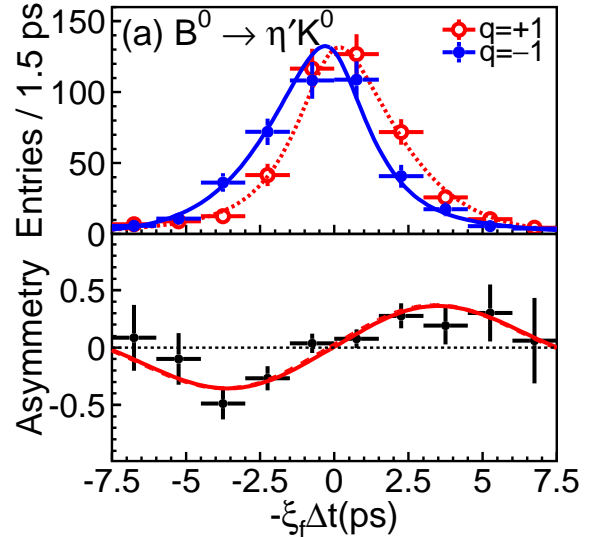


FIG. 3: Top: Belle background-subtracted Δt distributions for $B^0 \rightarrow \eta' K^0$ data (points with error bars for B^0 tags in red empty rectangles and \bar{B}^0 tags in blue solid circles), fit function (red dashed and blue solid lines for B^0 and \bar{B}^0 tagged events, respectively). Bottom: Asymmetry between B^0 and \bar{B}^0 tags, where the line represents the fit function.

TABLE II: Experimental measurements for the decays used as input to the GLNQ and GRZ calculations along with the coefficients that multiply the branching fractions for each mode and the 90% CL UL used for the recent GRZ calculation.

Mode	GLNQ Coeff.	GRZ Coeff.	BR or 90% CL ULs (10^{-6})			
			BABAR	Belle	CLEO	GRZ UL
$B^0 \rightarrow \eta\eta'$	0.96	0.87	$< 1.7[10]$	$< 4.0[13]$	$< 27[17]$	< 1.7
$B^0 \rightarrow \eta'\pi^0$	0.59	0.23	$< 2.1[10]$	$2.8 \pm 1.0 \pm 0.3[14]$	$< 5.7[18]$	< 2.4
$B^0 \rightarrow \eta'\eta'$	0.53		$< 2.4[11]$	$< 7.7[13]$	$< 47[17]$	< 2.4
$B^0 \rightarrow \eta\eta$	0.38		$< 1.8[11]$	$< 2.0[15]$	$< 18[17]$	< 1.8
$B^0 \rightarrow \eta\pi^0$	0.33	0.83	$< 1.3[10]$	$< 2.5[15]$	$< 2.9[18]$	< 1.3
$B^0 \rightarrow \pi^0\pi^0$	0.14		$1.48 \pm 0.26 \pm 0.12[12]$	$1.1 \pm 0.3 \pm 0.1[16]$	$< 4.4[19]$	< 1.58

V. THEORETICAL UNDERSTANDING

A. First-principles calculations

The theoretical expectation is that the value of C (indicative of direct CP violation) is near zero while for the SM, S should be nearly equal to $\sin 2\beta$. The world average for $\sin 2\beta$ is 0.675 ± 0.026 [9]. Small deviations from this value arise from tree or penguin $b \rightarrow u\bar{u}s$ amplitudes which have a different weak phase. The size of these deviations is expected to be $\sim \pm 0.01$; when calculation parameters are varied, the range is ± 0.03 [1].

B. SU(3)-related modes and theoretical limits

The above predictions are based on QCD factorization, PQCD, or SCET calculations. In 2003, Grossman, Ligeti, Nir, and Quinn (GLNQ) [4] showed that SU(3) and data from related B decays can be used to limit the size of the $b \rightarrow u\bar{u}s$ amplitudes. In their analysis, data from the six processes $B^0 \rightarrow \eta\eta'$, $B^0 \rightarrow \eta'\pi^0$, $B^0 \rightarrow \eta'\eta'$, $B^0 \rightarrow \eta\eta$, $B^0 \rightarrow \eta\pi^0$, and $B^0 \rightarrow \pi^0\pi^0$ are used. Measurements for these decays have improved substantially in recent years, with the current experimental situation summarized in Table II.

In this table, we also show the coefficients from the GLNQ calculation and order the modes from largest to smallest contributors to the limit on ΔS , deviation in the value of S from $\sin 2\beta$. We also show in red the three decays that are used in a more recent update of the GLNQ calculation by Gronau, Rosner, and Zupan (GRZ) [5], where it is assumed that exchange and penguin annihilation amplitudes are small. They find the allowed ranges of S and C shown in Fig. 4. The range from the $B^0 \rightarrow \eta\eta'$, $B^0 \rightarrow \eta'\pi^0$, and $B^0 \rightarrow \eta\pi^0$ decays is $-0.046 < \Delta S < 0.094$.

VI. SUMMARY

The *BABAR* and *Belle* experiments have each measured CP violation in the $B^0 \rightarrow \eta'K^0$ decay with significance greater than 5σ . *Belle* finds $S = 0.64 \pm 0.10 \pm 0.04$ and $C = 0.01 \pm 0.07 \pm 0.05$ while *BABAR* finds $S = 0.58 \pm 0.10 \pm 0.03$ and $C = -0.16 \pm 0.07 \pm 0.03$. These measurements are in good agreement with the expectations of the Standard Model. While the precision of these measurements is much better than was anticipated a decade ago, substantial improvement in precision is needed in order to check for non-SM effects.

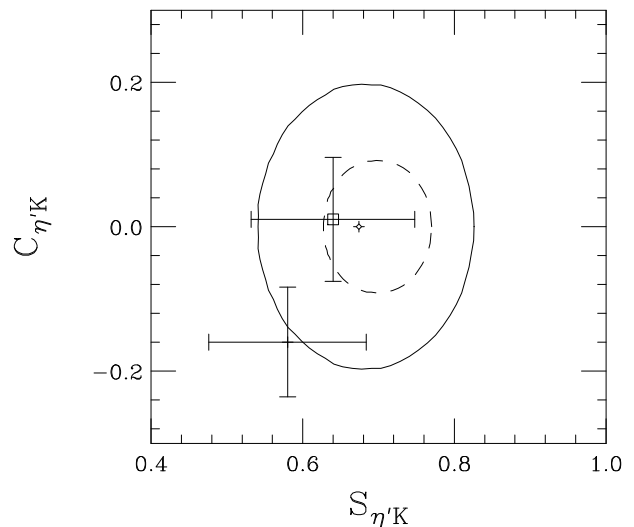


FIG. 4: The curves indicate the allowed ranges for S and C for $B^0 \rightarrow \eta'K^0$. The solid curve gives the bounds with the full GLNQ analysis with six inputs and the dashed line gives the more restrictive case where exchange and penguin-annihilation amplitudes are neglected so that only $B^0 \rightarrow \eta\pi^0$, $B^0 \rightarrow \eta'\pi^0$, and $B^0 \rightarrow \eta\eta'$ enter. The point (square) with error bars shows the *BABAR* (*Belle*) measured result. The small plotted point near the center shows the average of $c\bar{c}K^0$ measurements.

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